5420
625

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

June and September 1945 as
Memorandum Reports E5F20 & E5I12

SMOKING CHARACTERISTICS OF VARIOUS FUELS AS DETERMINED BY OPEN-CUP AND LABORATORY-BURNER SMOKE TESTS

By Earl R. Ebersole and Henry C. Barnett

Aircraft Engine Research Laboratory
Cleveland, Ohio

NACA

WASHINGTON

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

MEMORANDUM REPORT

for the

Air Technical Service Command, Army Air Forces

SMOKING CHARACTERISTICS OF VARIOUS FUELS AS DETERMINED BY OPEN-CUP AND LABORATORY-BURNER SMOKE TESTS

By Earl R. Ebersole and Henry C. Barnett

INTRODUCTION

At the request of the Air Technical Service Command, Army Air Forces, the Cleveland laboratory of the NACA is conducting tests in an I-16 combustion chamber to obtain performance data on a variety of hydrocarbon fuels.

Inasmuch as the smoking tendency of jet-propulsion fuels is of interest, a laboratory program has been conducted to obtain data on the smoking behavior of fuels. The results of open-cup smoke tests of 25 hydrocarbon fuels and of two series of prepared blends are presented. In order to determine the effect of fuel-air ratio as well as hydrocarbon class on the smoking behavior of fuels, 21 hydrocarbons were tested in a laboratory burner at fuel-air ratios ranging from 0.063 to 0.119. The results of these controlled-burning smoke tests are also presented. Correlation with data from full-scale jet-propulsion tests will be necessary to determine the applicability of the results.

APPARATUS AND TEST PROCEDURE

Open-cup tests. - The apparatus used in the open-cup tests is shown schematically in figure 1. A 3-milliliter sample of the fuel to be tested was placed in the open cup and ignited with an open flame. Smoke passing up the chimney absorbed a portion of the light beam from the light source. The effect of this light absorption on the photoelectric cell was registered by the recording microammeter. Before each test, the recording microammeter was adjusted to zero, if necessary, by varying the resistance in the lamp circuit. A check run was made on each fuel. The readings in microamperes were converted to percentage light absorbed by means of the calibration curve shown in figure 2. In the calibration of the recording instrument the light beam was interrupted with screens of varying mesh. The transmission through these screens was measured in a standard spectrophotometer using light with a wavelength of approximately 6000 A. The percentage light absorbed was then plotted against microampere readings to obtain the calibration curve.

Each of 25 hydrocarbon fuels was burned in an open cup in order to determine smoking characteristics. In each test the burning rate of the fuel was determined by measuring the time required to burn a 3-milliliter sample.

The fuels tested included representative hydrocarbons of the paraffinic, cycloparaffinic, olefinic, and aromatic classes as well as mixed fuels. Kerosene and the same kerosene from which aromatics had been removed were included in the mixed fuels tested. Two series of binary blends consisting of toluene in hydrogenated triisobutylene and triisobutylene in hydrogenated triisobutylene were tested over the range of concentrations from 0 to 100 percent.

Laboratory-burner tests. - The burner and the auxiliary apparatus used in the laboratory-burner tests are shown schematically in figure 3. Primary air was passed through the preheater at a constant flow rate of 4.1 $\pm$0.1 liters per minute. Secondary air was introduced at the base of the burner at a constant flow rate of 10.4 $\pm$0.2 liters per minute. The fuel to be tested was placed in a graduated burette, which was modified to give low and constant flow rates. (See reference 1.) The fuel was then admitted to the primary air stream and was vaporized and mixed with the primary air in the preheater at a temperature of 180° to 200° F above the boiling point of the hydrocarbon. After the fuel was ignited through the small hole in the side of the chimney, the hole was sealed off by means of a slip ring.

The flow rate of the air was maintained at 14.5 $\pm$0.3 liters per minute for all fuel-air ratios. The fuel-air ratio was varied by changing the flow rate of the fuel from the graduated burette. The rate of fuel flow was measured by determining to the nearest 0.01 minute the time required for a given volume (0.825 ml) to flow from the burette.

Each of 21 fuels including representative hydrocarbons of paraffinic, cycloparaffinic, olefinic, aromatic, and dicyclic classes was tested for smoking tendency at various fuel-air ratios. Smoke particle size was not measured in these tests.

DISCUSSION OF RESULTS

Open-cup tests. - The results of the open-cup smoke tests are presented in table I. Smoke is reported as percentage light absorbed. Total smoke from a 3-milliliter sample was determined by measuring the area under the curve traced by the recording microammeter. Values of average smoke were computed by dividing the total smoke by the burning time. Values of peak smoke were obtained by visually averaging the deflections in the highest portion of the curve.

The data in table I show that, with the exception of the cycloparaffins, the fuels of a given hydrocarbon class gave readings within a range of 8 percent light absorbed and that the aromatics gave higher readings than the other classes. The greater smoking tendency of the aromatics can be further shown by the tests on kerosene and dearomatized kerosene. Kerosene gave a peak value of 21 percent light absorbed as compared with 5 percent for dearomatized kerosene.

In order to ascertain the effect of burning rate on the smoking tendency, average smoke (percentage light absorbed) was plotted against burning rate (grams per min) in figure 4. Both test run and check run for each fuel are plotted. The five-carbon ring cycloparaffins are not shown in this figure because data were obtained for only two compounds in this series. It can be seen in table I that considerable difference in smoking tendency was found between the five-carbon ring and the six-carbon ring cycloparaffins. The fuels tested (fig. 4) show that the type of hydrocarbon exerts a much greater influence on the smoking tendency than does the burning rate of the fuel.

Figure 5 shows the variation of the burning rate of the fuels with boiling point. As in figure 4 both test and check runs are plotted. For the fuels tested, the burning rate of hydrocarbons within a given class decreased with increasing boiling point. It is of interest that two fuels of different classes with different boiling points will burn at the same rate; for example, from the curves of figure 5, a paraffinic hydrocarbon with a boiling point of 176° F will burn at approximately the same rate as an aromatic hydrocarbon with a boiling point of 305° F.

In order to show the relation of smoking tendency and composition for fuels having equal boiling points, tests were made on blends of triisobutylene in hydrogenated triisobutylene. A linear relation was obtained. (See fig. 6.) Figure 7 shows the results of tests of two fuels (toluene and hydrogenated triisobutylene) having different boiling points.

Laboratory-burner tests. - The results of the laboratory-burner smoke tests are presented in table II together with the boiling point and the stoichiometric fuel-air ratio of each fuel tested. At the maximum fuel-air ratios that would support combustion in the burner no smoke was obtained for paraffinic, cycloparaffinic, or olefinic hydrocarbons with the exception of triisobutylene, which gave detectable smoke at a fuel-air ratio of 0.102.

Aromatic and dicyclic hydrocarbons began smoking at approximately their stoichiometric fuel-air ratios. Figures 8 and 9 show the variation of smoke (percentage light absorbed) with fuel-air ratio for aromatic and dicyclic hydrocarbons, respectively. Kerosene is also included in figure 9. Within experimental error the smoking tendency appears to be a linear function of the fuel-air ratio for aromatic and dicyclic hydrocarbons. Comparison of figures 8 and 9 indicates that the smoking tendency of naphthalenic hydrocarbons is greater than that of aromatic hydrocarbons.

SUMMARY OF RESULTS

The data obtained from an investigation of the smoking characteristics of 25 hydrocarbons indicate that for uncontrolled burning in an open cup:

1. The smoking tendency of a hydrocarbon fuel is more dependent upon the type of hydrocarbon than upon its boiling point or burning rate.

2. The burning rate of hydrocarbons within a given class tended to decrease with increasing boiling point.

3. The smoking tendency of a commercial kerosene was about four times that of the same kerosene from which aromatics had been removed.

Results obtained from controlled-burning smoke tests indicate that:

1. The smoking tendency of hydrocarbon fuels is dependent upon both the class of hydrocarbon and the fuel-air ratio.

2. Within experimental error the smoking tendency of aromatic and dicyclic hydrocarbons is a linear function of the fuel-air ratio.

The following table summarizes the data obtained:

OPEN-CUP SMOKE TESTS

Class	Boiling point (°F)	Hydrogen-carbon ratio	Peak smoke (percent light absorbed)	Burning rate (grams/min)
Paraffins	122-230	0.189-0.196	10-15	0.69-1.07
Six-carbon ring cycloparaffins	178-279	.177	8-13	.62- .85
Five-carbon ring cycloparaffins	122-161	.167	23-31	.97-1.13
Olefins	101-172	.167	40-47	.97-1.33
Aromatics	230-323	.095- .111	68-75	.75-1.36

LABORATORY-BURNER SMOKE TESTS

Hydrocarbon class	Boiling-point range (°F)	Stoichiometric fuel-air ratio	Fuel-air-ratio range	Smoke (percent light absorbed)
Paraffins	178-350	0.065-0.066	0.064-0.114	0
Cyclohexanes	178-270	.067	.073- .115	0
Olefins	133-350	.067	.062- .109	0-3
Aromatics	175-465	.070- .075	.063- .108	0-47
Dicyclics	365-605	.069- .077	.069- .119	3-80

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, June 20, 1945; Sept. 12, 1945.

REFERENCE

1. Zentner, E. Thomas: Delivery of Liquids at Low and Constant Rates. Ind. and Eng. Chem. (Anal. ed.), vol. 16, no. 7, July 21, 1944, pp. 471-472.

TABLE I. - RELATIVE SMOKING CHARACTERISTICS OF

VARIOUS FUELS BURNED IN OPEN CUP

Class of hydro-carbon	Compound	Peak smoke observed (percent light absorbed)	Average smoke (percent light absorbed)	Total smoke (area in sq in.)	Rate of burning (grams/min)	Boiling point (°F)	Hydrogen-carbon ratio
Paraffins	2,2-Dimethyl-	11	10	1.4	1.052	122	0.196
	butane	13	11	1.7	1.076		
	2,3-Dimethyl-	11	11	2.0	.941	137	.196
	butane	13	10	1.7	.978		
	2,2,3-Tri-	15	11	2.2	.805	178	.192
	methylbutane	15	11	2.4	.779		
	2,3-Dimethyl-	10	7	1.4	.772	193	.192
	pentane	10	6	1.4	.723		
	2,2,3-Tri-	13	10	2.5	.679	230	.189
	methylpentane	11	8	2.0	.688		
Cyclo-paraffins	Cyclopentane	26	20	3.6	1.125	122	0.167
		23	18	3.3	1.125		
	Methylcyclo-	31	26	5.4	.965	161	.167
	pentane	31	24	5.8	.965		
	Cyclohexane	8	8	1.8	.825	178	.167
		10	7	1.5	.849		
	Methyl-	11	8	2.0	.755	212	.167
	cyclohexane	13	10	2.5	.787		
	Ethyl-	11	9	2.8	.617	269	.167
	cyclohexane	13	8	2.3	.517		
Olefins	Trimethyl-	42	37	5.8	1.325	101	0.167
	ethylene	44	37	5.8	1.325		
	2,3-Dimethyl-	44	37	6.4	1.223	133	.167
	butene-1	43	37	6.6	1.223		
	2,3-Dimethyl-	40	33	6.9	1.026	164	.167
	butene-2	42	35	7.6	.968		
	Triptene	46	38	8.2	1.063	172	.167
		47	38	8.2	1.063		
Cyclo-olefins	Methyl-	50	41	8.0	1.323	216	0.143
	cyclohexene	47	37	8.1	1.142		
Aromatics	Toluene	71	50	10.7	1.363	230	0.095
		68	49	11.2	1.280		
	Xylene	68	52	18.3	.844	279-288	.104
	isomers	75	57	19.1	.893		
	_n_-Propyl-	70	52	18.7	.816	320	.111
	benzene	70	54	19.7	.816		
	_m_-Ethyl-	70	51	19.4	.763	323	.111
	toluene	72	55	22.7	.745		
Mixed fuels	Virgin base stock	21	---------	-----	0.698	115-298	---------
	Hot-acid octanes	13	---------	-----	.652	174-257	---------
	Triisobutylene[a]	35	---------	-----	-------	340-350	---------
	Hydrogenated triisobutylene[a]	16	---------	-----	-------	335-350	---------
	Kerosene	21	---------	-----	-------	302-486	---------
	Kerosene (dearomatized)	5	---------	-----	-------	-------	---------

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

[a]Listed as mixed fuels because their purity is questionable.

TABLE I. - SMOKING CHARACTERISTICS OF HYDROCARBON FUELS

DETERMINED FROM CONTROLLED-BURNING TESTS

Class of hydrocarbon	Compound	Boiling point (°F)	Stoichi-ometric fuel-air ratio	Fuel-air-ratio range	Hydrogen-carbon ratio	Smoke (percent light absorbed)
Paraffins	Triptane	178	0.065	0.067-0.103	0.191	0
	Diisopropyl	137	.065	.064- .071	.195	0
	Neohexane	122	.065	.070- .085	.195	0
	2,2,3-Trimethyl-pentane	230	.066	.074- .083	.188	0
	Hydrogenated triisobutylene	335-350	.066	.083- .114	.181	0
Cyclohexanes	Cyclohexane	178	.067	.073- .093	.167	0
	Ethylcyclo-hexane	269	.067	.073- .115	.167	0
Olefins	2,3-Dimethyl-butene-1	133	.067	.080- .096	.167	0
	2,3,3-Trimethyl-butene-1	172	.067	.062- .090	.167	0
	Triisobutylene	340-350	.067	.092- .109	.167	0-3
Aromatics	Benzene	176	.075	.063- .104	.083	0-37
	Ethylbenzene	277	.073	.076- .100	.104	3-34
	Isopropylbenzene	306	.072	.063- .100	.111	0-32
	1,2,4-Trimethyl-benzene	337	.072	.076- .108	.111	3-47
	Triisopropyl-benzene	465	.070	.073- .107	.133	5-44
Dicyclics	1-Methyl-naphthalene	473	.077	.073- .114	.076	3-80
	Dimethyl-naphthalene	511	.075	.078- .102	.083	11-59
	Monoamyl-naphthalene	535-608	.073	.069- .097	.101	9-50
	Tetralin	405	.073	.076- .108	.101	7-61
	Decalin	365-382	.069	.084- .119	.150	3-18
Mixed fuels	Kerosene	302-486	--------	.060- .108	---------	0-5

NATIONAL ADVISORY
COMMITTEE FOR AERONAUTICS

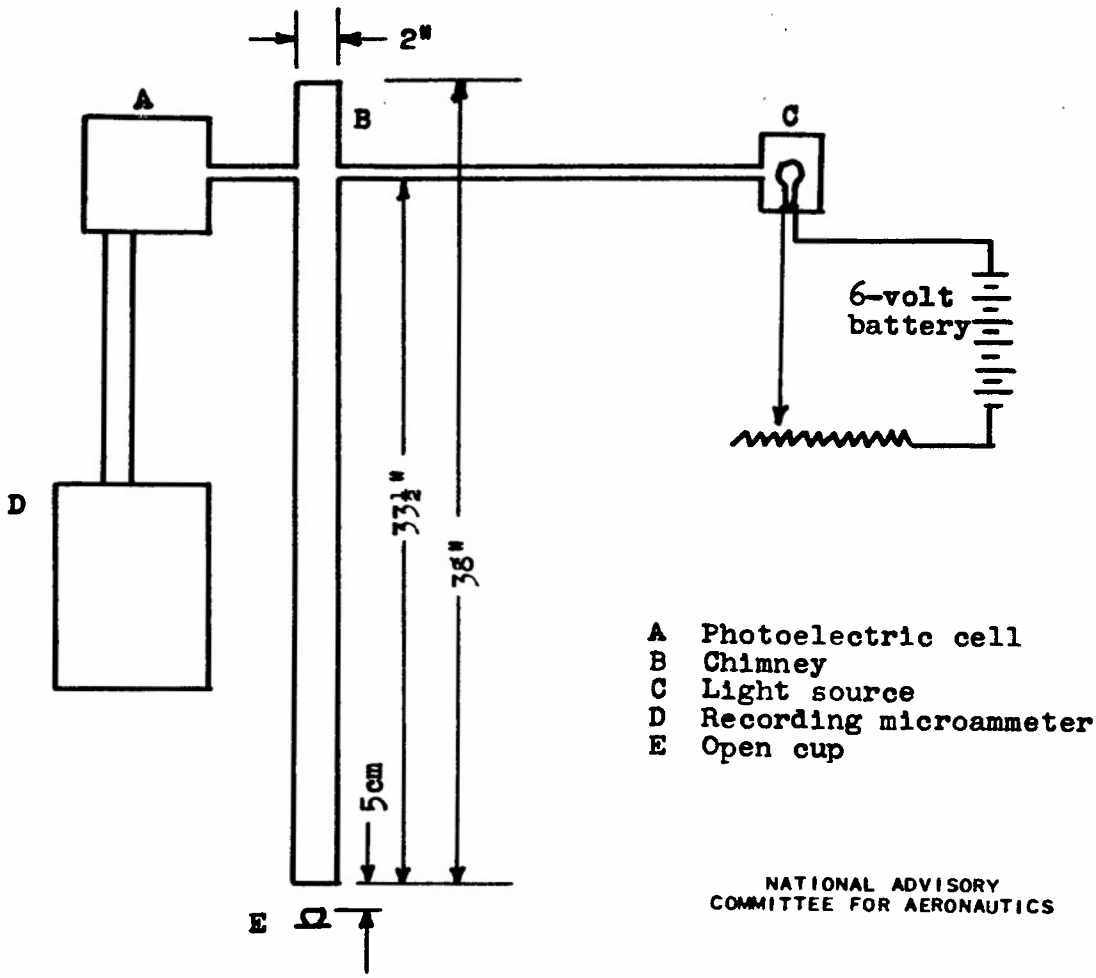

Figure 1. - Schematic diagram of apparatus for open-cup smoke tests.

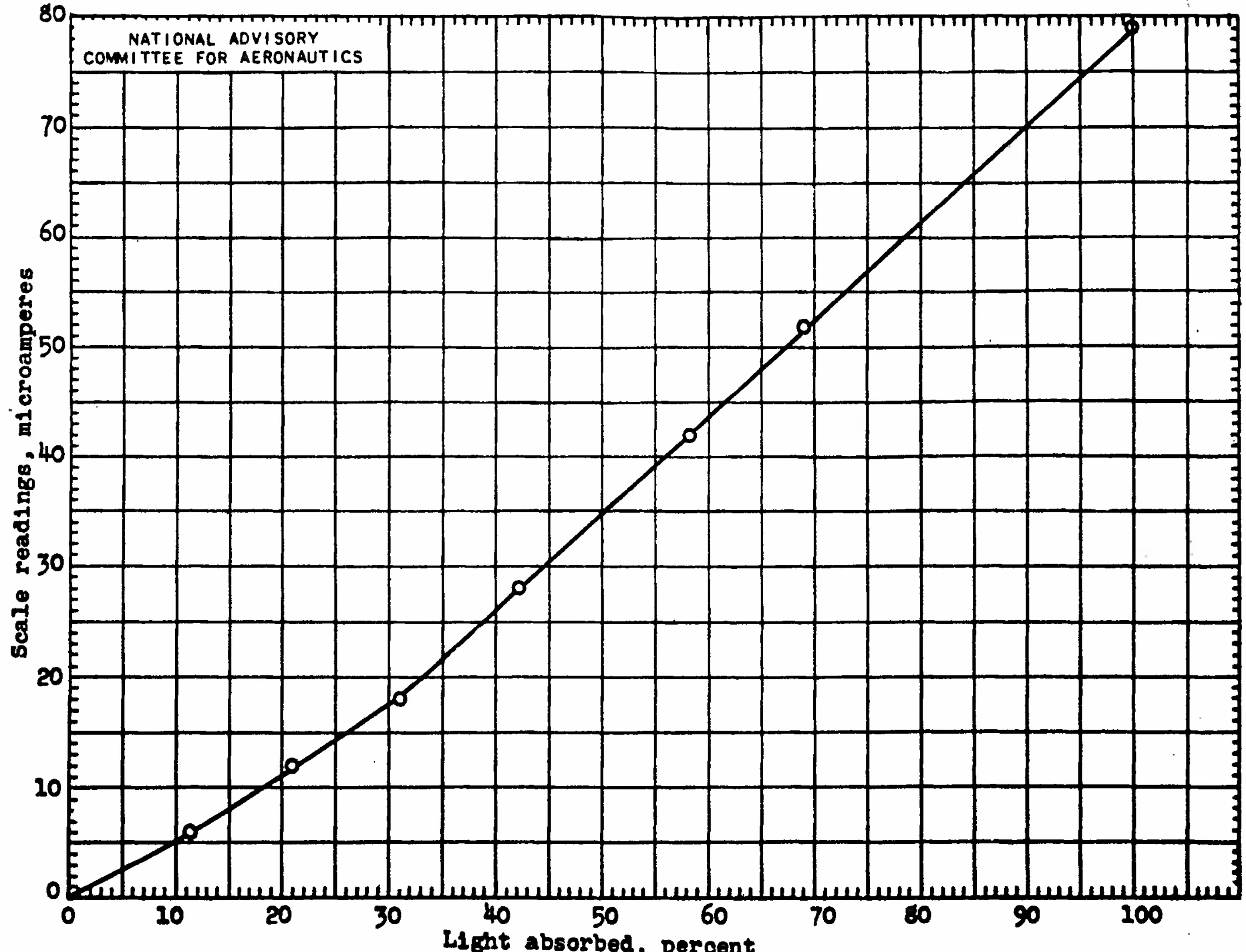

Figure 2. - Calibration curve for photocell.

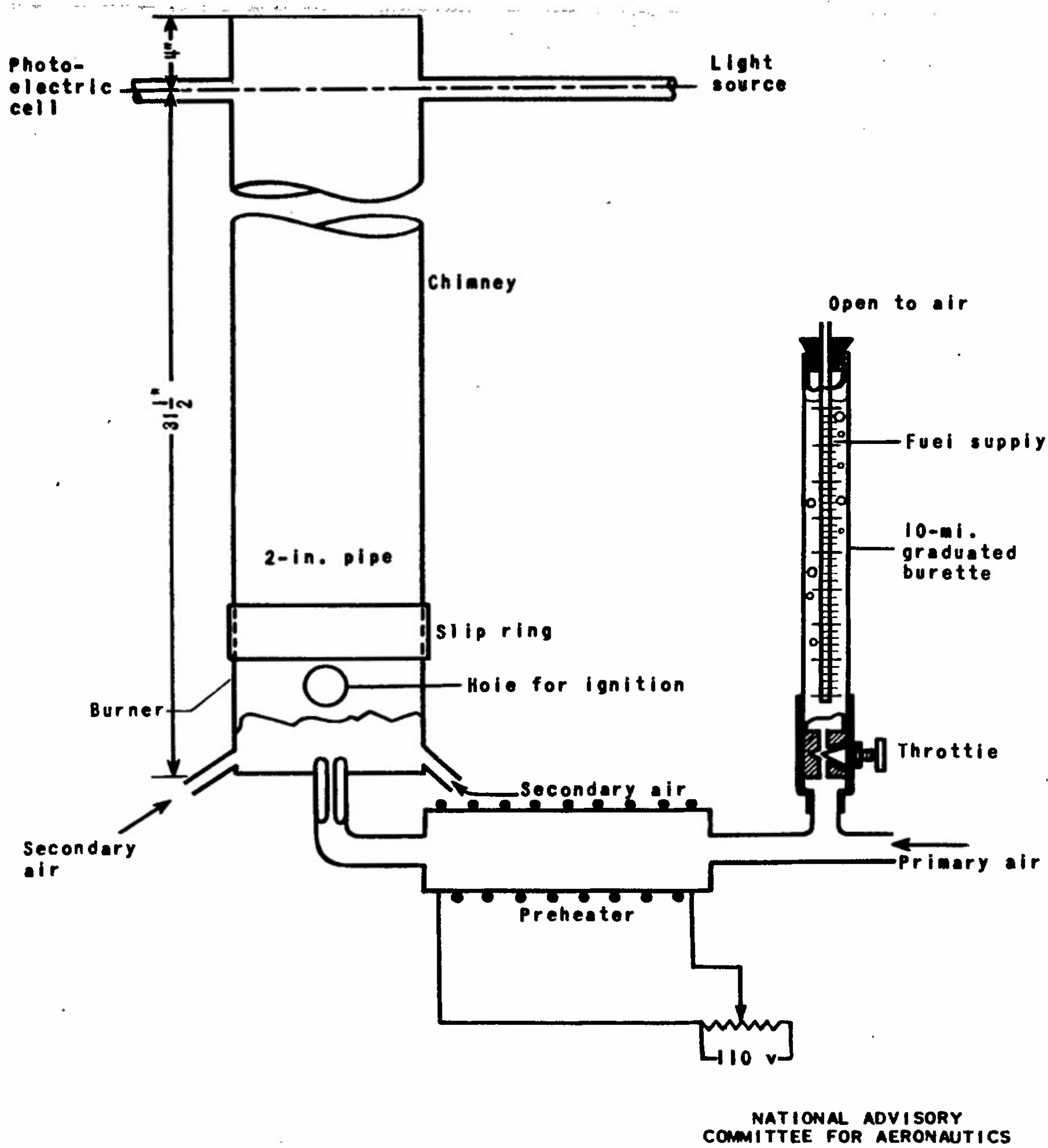

Figure 3. - Schematic diagram of burner and auxiliary apparatus.

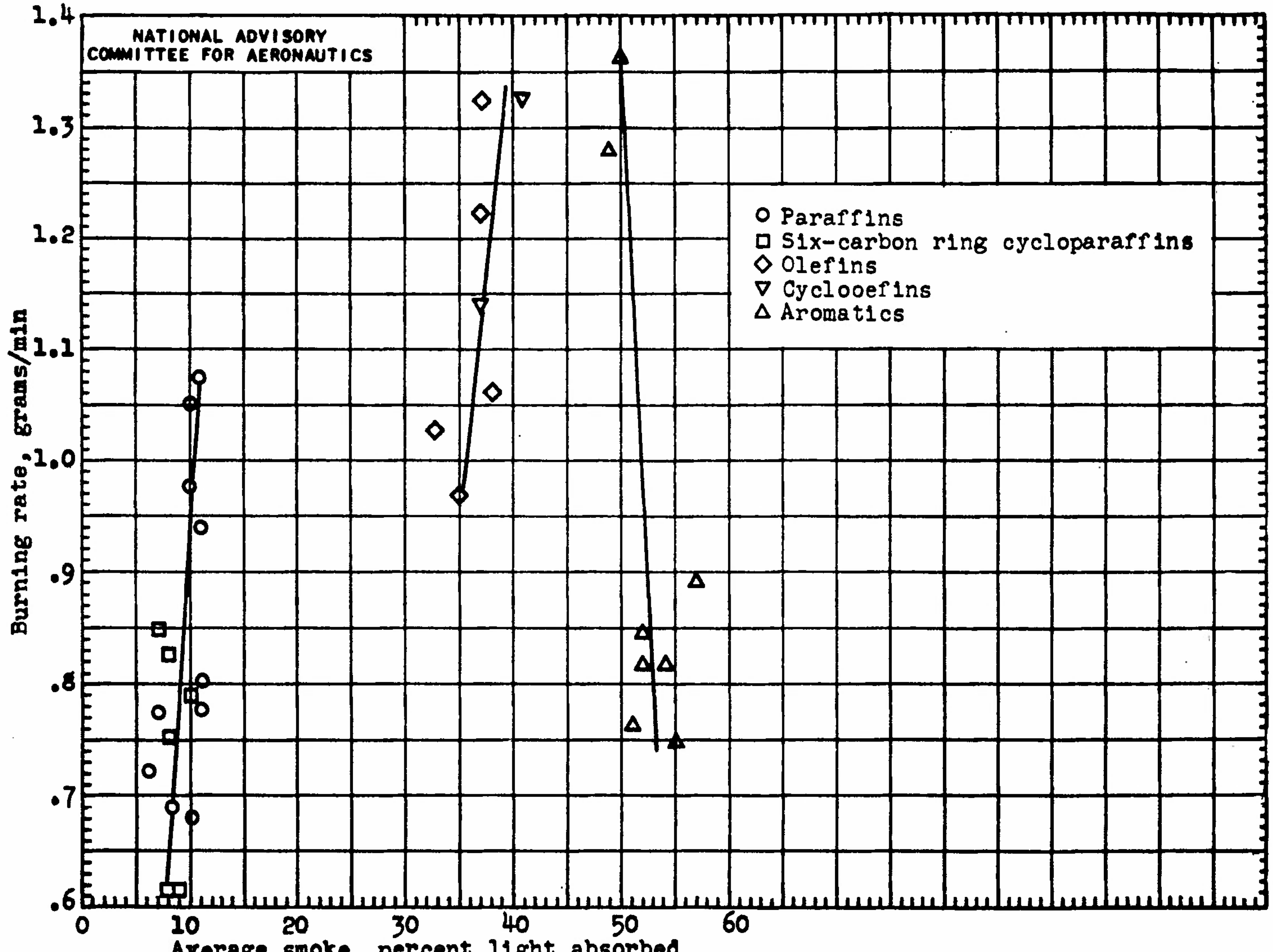

Figure 4. - Effect of burning rate on smoking tendency of hydrocarbon fuels.

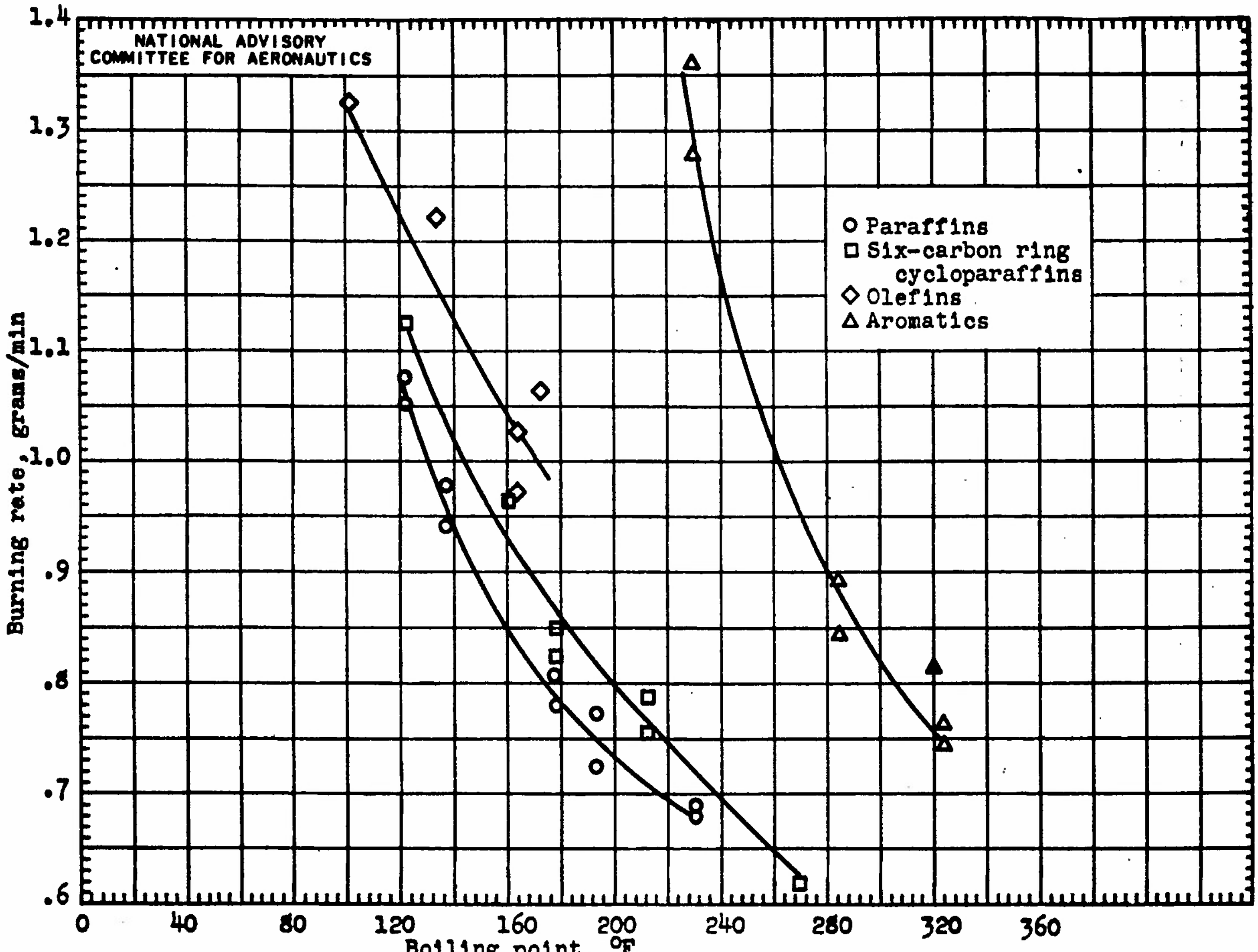

Figure 5. - Variation of burning rate with boiling point.

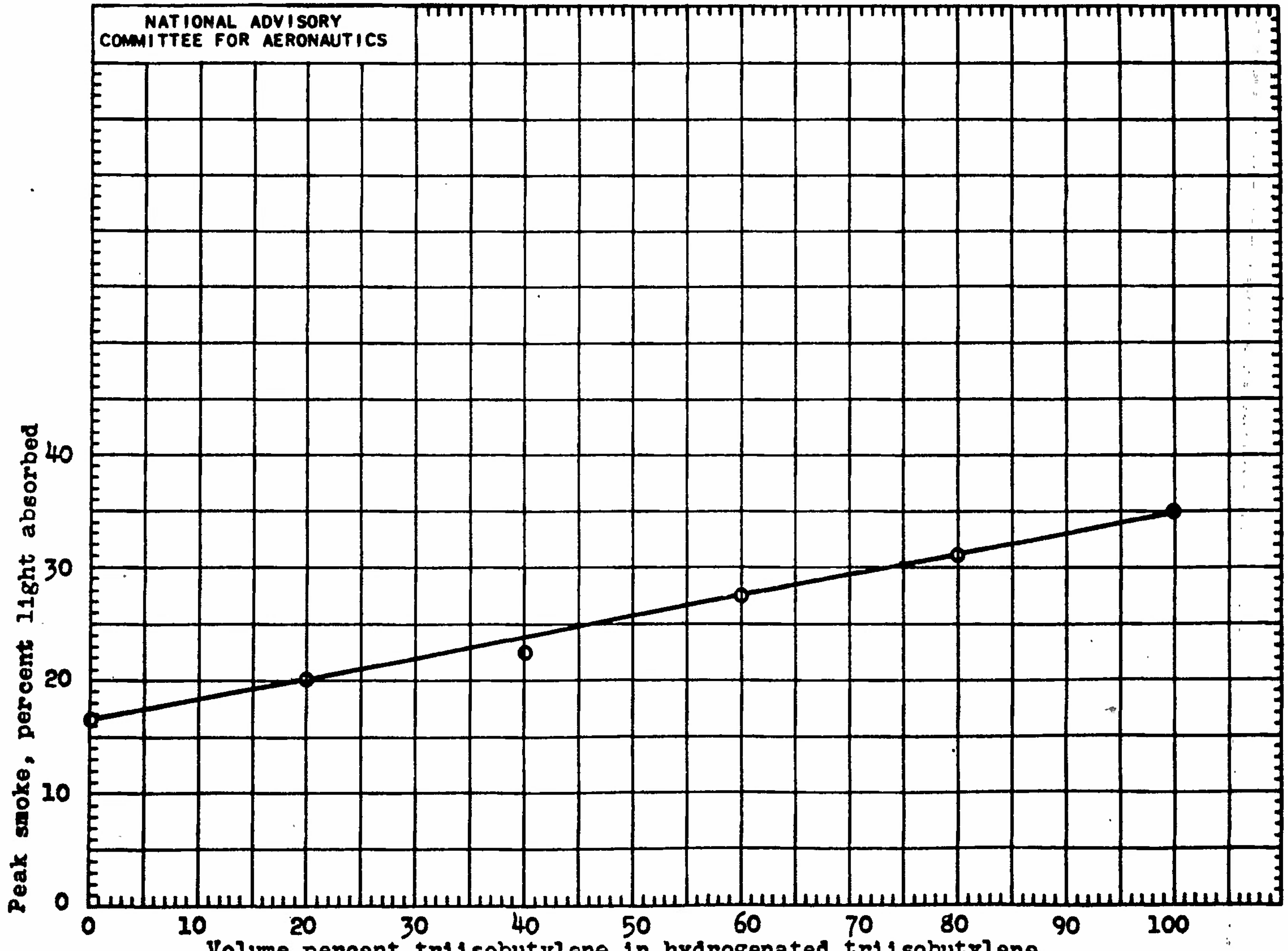

Figure 6. - Variation of smoking tendency with concentration for blends of two fuels with similar boiling points.

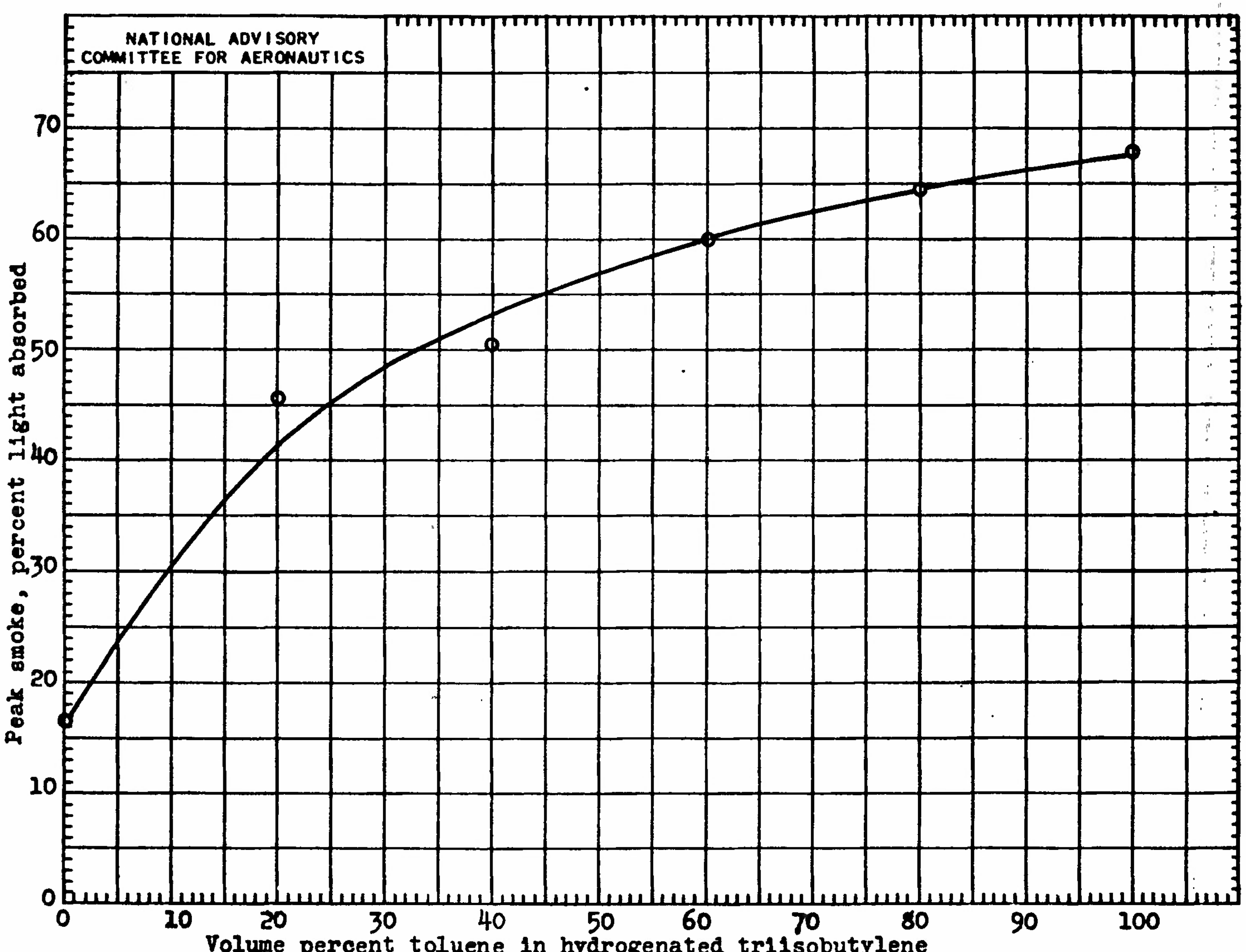

Figure 7. - Variation of smoking tendency with concentration for blends of two fuels with different boiling points.

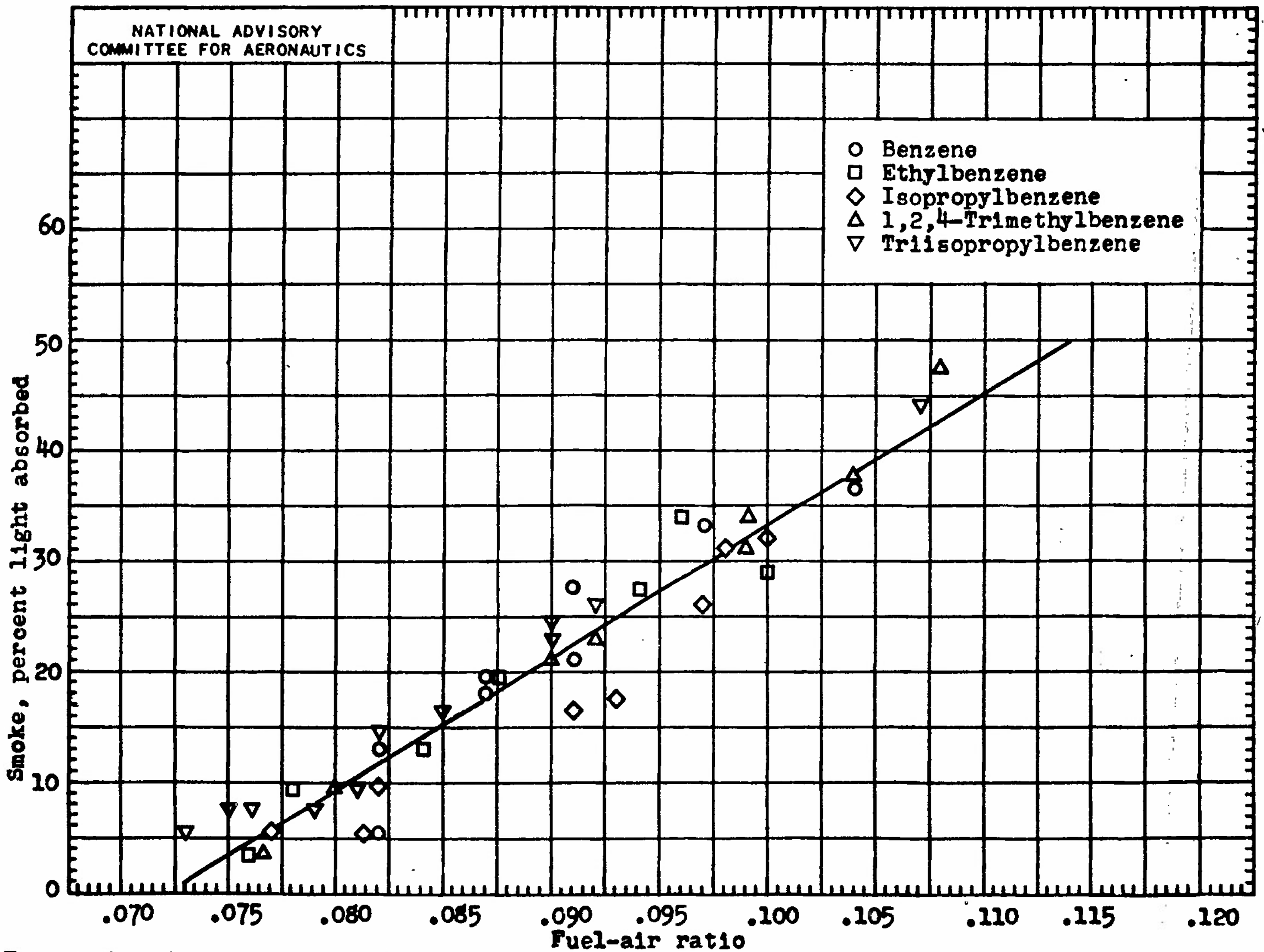

Figure 8. - Variation of smoke with fuel-air ratio for aromatic hydrocarbons.

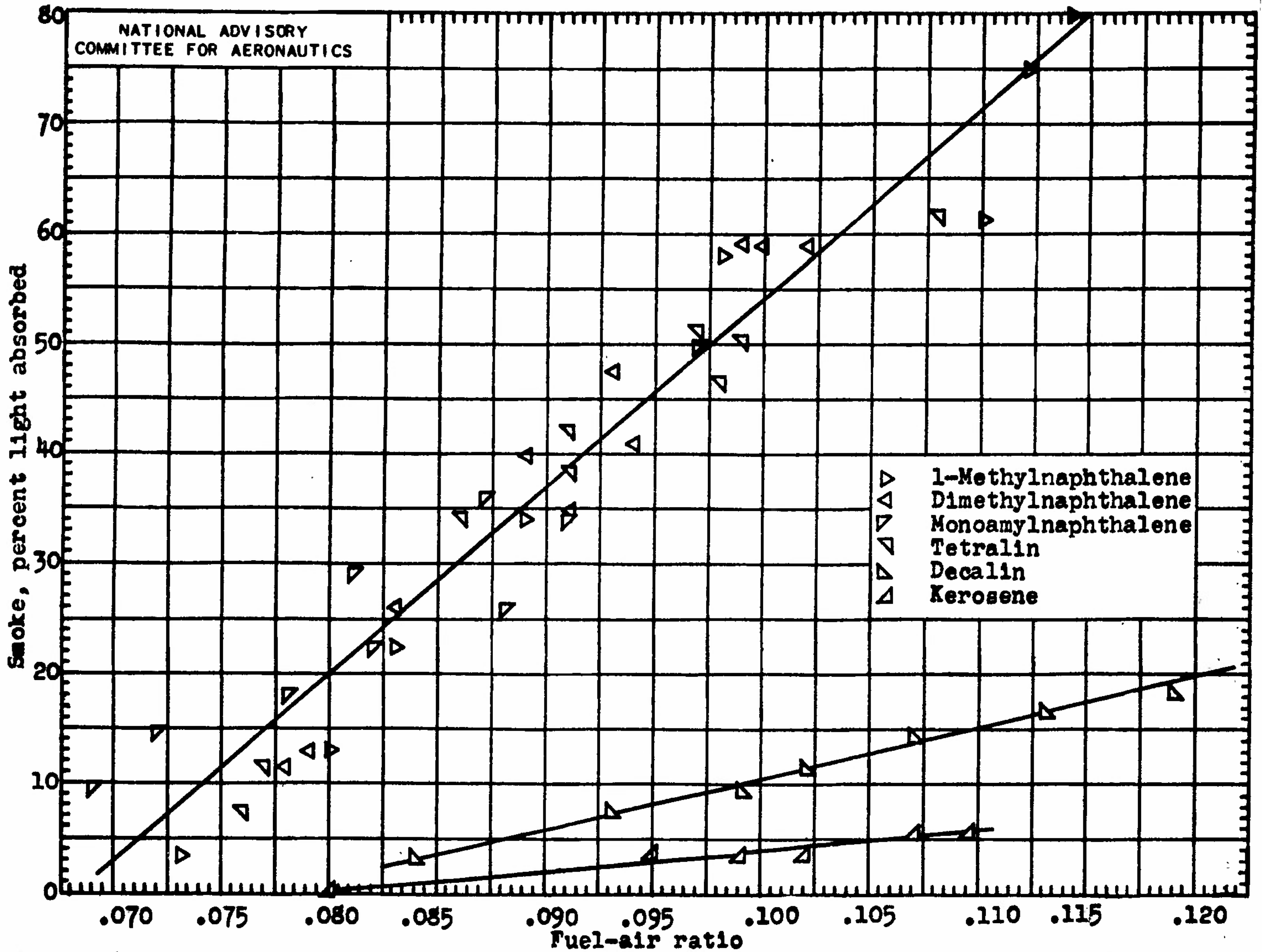

Figure 9. - Variation of smoke with fuel-air ratio for dicyclic hydrocarbons and kerosene.

UNCLASSIFIED [redacted]

TSDIN FORM 60 B (13 MAR 47)

C-12-2-3

ATI- 12418

ORIG. AGENCY [redacted]

MR-E5F20 [redacted]

REVISION

Eberaole, Earl
Barnett, Henry

AUTHOR(S)

DIVISION: Fuels and Lubricants (12) 10

SECTION: Liquid Fuels (2) 2

CROSS REFERENCES: Fuels, Liquid - Smoking characteristics (42679)

OVER

AMER. TITLE: Smoking characteristics of various fuels

FORG'N. TITLE:

ORIGINATING AGENCY: National Advisory Committee for Aeronautics, Washington, D. C.

TRANSLATION:

COUNTRY	LANGUAGE	FORG'N. CLASS	U. S. CLASS.	DATE	PAGES	ILLUS.	FEATURES
U.S.	Eng.		[redacted]	Jun'45	12	8	table, diagr, graphs

ABSTRACT

Investigation of smoking characteristics of uncontrolled burning of hydrocarbons in an open cup showed that smoking tendency of a hydrocarbon fuel is much more dependent upon the type of hydrocarbon than upon its boiling point or burning rate. The burning rate tended to decrease with increasing boiling point within a given class of hydrocarbons. Smoking tendency of a commercial kerosene was about four times that of the same kerosene from which aromatics had been removed.

NOTE: Requests for copies of this report must be addressed to N.A.C.A., Washington, D. C.

UNCLASSIFIED PER AUTHORITY: INDEX
OF NACA TECHNICAL PUBLICATIONS
DATED 31 DECEMBER 1947.